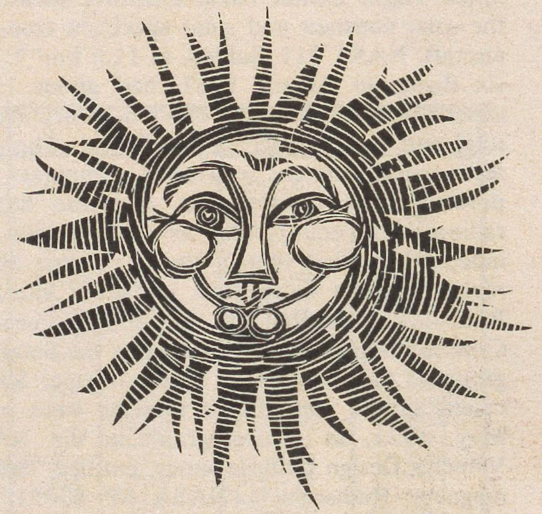
EVALUATING THE LIGHT FROM THE SUN

High-altitude observations, made in response to space-age needs, indicate the need for reassessing some long-accepted values based on previous ground-based measurements of the sun's energy and spectral distribution.



by Matthew P. Thekaekara

OPTICAL SPECTRA AS A FIELD OF RESEARCH began with the discovery by Sir Isaac Newton that the white light of the sun is made up of many different colors. The energy from the sun and its spectral distribution has been and still is a fruitful and elusive field of research.

Recent measurements from high altitude observing platforms have produced converging evidence that the values accepted earlier need significant revisions. The values most commonly accepted in the United States had been those proposed in 1954 by Francis S. Johnson.[1] These values were based mainly on an analysis of the ground-based data of the Smithsonian Institution, supplemented for the ultraviolet by rocket data of the Naval Research Laboratory.

In all ground-based measurements, the dust, haze, and smoke of the atmosphere, the permanent gases and, above all, the highly variable and absorbent water vapor are a source of uncertainty. These measurements are made at varying zenith angles of the sun and the readings are extrapolated to what they would have been in the absence of the earth's atmosphere. Since the extinction due to the atmosphere varies with wavelengths, the spectral irradiance is determined in narrow wavelength ranges and the integral energy is computed to give the solar constant. The solar constant, as is well known, is the energy due to the sun incident on unit area exposed normally to the sun's rays at the average sun-earth distance in the absence of the earth's atmosphere. The solar spectral irradiance is the distribution of this energy as a function of wavelength.

Evaluations of the solar constant derived from ground based measurements cover a wide range from 1323 $W \cdot m^{-2}$ of Parry Moon (1940) to 1428 $W \cdot m^{-2}$ of Stair and Johnston (1954) and 1418 $W \cdot m^{-2}$ of Makarova and Kharitonov of USSR (1969). F. S. Johnson's value was 1395 $W \cdot m^{-2}$. All earlier observers have also derived zero air mass solar spectral irradiance curves based on their data. The differences between authors for spectral irradiance values are even greater than for the solar constant. In the ultraviolet range discrepancies are as high at 40%. In the wavelength range longer than 0.7 μm, which contains more than half of the solar energy, the water vapor of the atmosphere is a strong absorbent and most authors, following the lead of Parry Moon, had assumed the solar spectrum to be that of a 6000K blackbody.

Space-age requirements

With the advent of the space age the need for a more reliable set of values of the solar constant and the solar spectrum began to be realized. The temperature equilibrium of satellites and space probes, the electrical output of solar cells, the degradation of surface coatings, the torques due to radiation pressure, the irradiance levels to be maintained in solar simulation chambers for pre-launch testing of satellites, all require design values about the sun's energy, both total and spectral. These are also necessary in many areas of astronomy, astrophysics, meteorology, optics, spectroscopy, geophysics, illumination engineering, etc.

A group of experimenters from NASA Goddard Space Flight Center made extensive measurements of the solar constant and solar spectrum from a research aircraft, NASA 711 Galileo, at 11.6 km[2, 3]. They made six flights in August 1967, had about 15 hours of observation and used 11 different instruments, five for total and six for spectral irradiance. The instruments represented different measuring techniques and incorporated some of the best available techniques in radiometry. Their results, as well as data from other independent observers in the U. S. and abroad, were reviewed by a Committee on Solar Electromagnetic Radiation sponsored by the Space Vehicles Design Criteria Program of NASA and by the Solar Simulation group of the Institute of Environmental Sciences. The results of the committee's findings were published in May, 1971, as a monograph in the NASA Space Vehicles Design Criteria series, entitled "Solar Electromagnetic Radiation," (NASA SP 8005).[4] They are also being proposed for engineering use in general by the American Society of Testing Materials and the Institute of Environmental Sciences,[5] and are currently being used for design and testing in many laboratories. This paper will present these values and review briefly how they were derived.

The committee's values

The value of the solar constant is 1353 $W \cdot m^{-2}$. The estimated error is ±21 $W \cdot m^{-2}$. In units of calories $\cdot cm^{-2} \cdot min^{-1}$ the value is 1.940. This is 3% lower than the Johnson value. The independent measurements on the basis of which the solar constant was derived are shown in Table I. They are all values based on measurements from high altitude observing platforms, aircraft or balloons, or from spacecraft. The instruments were total radiation detectors. The radiation scales to which these values are referred are that of a blackbody radiator for the Hy-Cal pyrheliometer, the scale of absolute electrical units for the GSFC cone and JPL cavity radiometer, and the international pyrheliometric scale IPS '56 for the five other instruments. The three scales are in agreement within the limit of accuracy of these measurements.

The zero air mass solar spectral irradiance curve is given in tabular form in Table II and graphically in Figure 1. In the wavelength range of 0.3 to 15μm, which contains nearly 99% of the energy of the sun, these values are based mainly on the measurements made by the GSFC team from the research aircraft. The instruments used were a Perkin-Elmer model 112 spectrometer with a lithium fluoride window, a Leiss double quartz prism monochromator, a filter radiometer, a polarization type interferometer and, for the infrared range beyond 4μm, a Michelson type interferometer. In the wavelength range 0.3 to 2.6μm an independent set of data are available from the Eppley-JPL measurements, made with a filter radiometer during several series of flights of Convair 990 and B57B and one flight above the ozonosphere by the X-15 rocket aircraft.[6] In the wavelength range above 0.7μm the Eppley-JPL integrated value was practically

Table I

Measurements from which solar constants were derived.

Platform	Detector	Year	Solar Constant $W \cdot cm^{-2}$
NASA 711 Aircraft	GSFC Hy-Cal Pyrheliometer	1967	1358
NASA 711 Aircraft	GSFC Ångström 7635	1967	1349
NASA 711 Aircraft	GSFC Ångström 6618	1967	1343
NASA 711 Aircraft	GSFC Cone Radiometer	1967	1358
Soviet Balloon	U. of Leningrad Actinometer	1961-1968	1353
U. of Denver Balloon	Eppley Normal Incidence Pyrheliometer	1969	1338
X-15, B57B, CV990 Aircraft	Eppley Normal Incidence Pyrheliometer	1966-1968	1360
Mariner VI & VII Spacecraft	JPL Cavity Radiometer	1969	1353
JPL Balloon	JPL Cavity Radiometer	1968-1969	1368
		Average	1353

TABLE II

SOLAR SPECTRAL IRRADIANCE - PROPOSED STANDARD CURVE

λ - Wavelength in micrometers

E(λ) - Solar spectral irradiance averaged over small bandwidth centered at λ, in $W \cdot m^{-2} \cdot \mu m^{-1}$

E(o-λ) - Area under the solar spectral irradiance curve in the wavelength range 0 to λ in $W \cdot m^{-2}$

D(o-λ) - Percentage of the solar constant associated with wavelengths shorter than λ

Solar Constant - 1353 $W \cdot m^{-2}$

λ	E(λ)	E(o-λ)	D(o-λ)	λ	E(λ)	E(o-λ)	D(o-λ)	λ	E(λ)	E(o-λ)	D(o-λ)
.120	.100	.0059992	.00044	.525	1852	352.591	26.059	1.70	202	1221.23	90.261
.140	.030	.0072999	.00053	.530	1842	361.826	26.742	1.75	180	1230.78	90.967
.150	.07	.00780	.00057	.535	1818	370.976	27.418	1.80	159	1239.25	91.593
.160	.23	.00930	.00068	.540	1783	379.979	28.084	1.85	142	1246.78	92.149
.170	.63	.01360	.00100	.545	1754	388.821	28.737	1.90	126	1253.48	92.644
.180	1.25	.02300	.00169	.550	1725	397.519	29.380	1.95	114	1259.48	93.088
.190	2.71	.04280	.00316	.555	1720	406.131	30.017	2.00	103	1264.90	93.489
.200	10.7	.10985	.00811	.560	1695	414.669	30.648	2.10	90	1274.55	94.202
.210	22.9	.27785	.02053	.565	1705	423.169	31.276	2.20	79	1283.00	94.826
.220	57.5	.67985	.05024	.570	1712	431.711	31.907	2.30	69	1290.40	95.373
.225	64.9	.98585	.0728	.575	1719	440.289	32.541	2.4	62.0	1296.95	95.8580
.230	66.7	1.31485	.0971	.580	1715	448.874	33.176	2.5	55.0	1302.80	96.2903
.235	59.3	1.62985	.1204	.585	1712	457.441	33.809	2.6	48.0	1307.95	96.6710
.240	63.0	1.93560	.1430	.590	1700	465.971	34.439	2.7	43.0	1312.50	97.0073
.245	72.3	2.27385	.1680	.595	1682	474.426	35.064	2.8	39.0	1316.60	97.3103
.250	70.4	2.63060	.1944	.600	1666	482.796	35.683	2.9	35.0	1320.30	97.5838
.255	104	3.06660	.2266	.605	1647	491.079	36.295	3.0	31.0	1323.60	97.8277
.260	130	3.65160	.2698	.610	1635	499.284	36.902	3.1	26.0	1326.45	98.0383
.265	185	4.43910	.3280	.620	1602	515.469	38.098	3.2	22.6	1328.88	98.2179
.270	232	5.48160	.4051	.630	1570	531.329	39.270	3.3	19.2	1330.97	98.3724
.275	204	6.5716	.4857	.64	1544	546.899	40.421	3.4	16.6	1332.76	98.5047
.280	222	7.6366	.5644	.65	1511	562.174	41.550	3.5	14.6	1334.32	98.6200
.285	315	8.9791	.6636	.66	1486	577.159	42.657	3.6	13.5	1335.73	98.7238
.290	482	10.9716	.8109	.67	1456	591.869	43.744	3.7	12.3	1337.02	98.8192
.295	584	13.6366	1.0078	.68	1427	606.284	44.810	3.8	11.1	1338.19	98.9056
.300	514	16.3816	1.2107	.69	1402	620.429	45.855	3.9	10.3	1339.26	98.9847
.305	603	19.1741	1.4171	.70	1369	634.284	46.879	4.0	9.5	1340.25	99.0579
.310	689	22.4041	1.6558	.71	1344	647.849	47.882	4.1	8.7	1341.16	99.1252
.315	764	26.0366	1.9243	.72	1314	661.139	48.864	4.2	7.8	1341.98	99.1861
.320	830	30.0216	2.2188	.73	1290	674.159	49.826	4.3	7.1	1342.73	99.2412
.325	975	34.5341	2.552	.74	1260	686.909	50.769	4.4	6.50	1343.4141	99.291507
.330	1059	39.6191	2.928	.75	1235	699.384	51.691	4.5	5.90	1344.0341	99.337331
.335	1081	44.9691	3.323	.76	1211	711.614	52.595	4.6	5.30	1344.5941	99.378721
.340	1074	50.3566	3.721	.77	1185	723.594	53.480	4.7	4.80	1345.0991	99.416045
.345	1069	55.7141	4.117	.78	1159	735.314	54.346	4.8	4.50	1345.5641	99.450413
.350	1093	61.1191	4.517	.79	1134	746.779	55.194	4.9	4.10	1345.9941	99.482195
.355	1083	66.5591	4.919	.80	1109	757.994	56.023	5.0	3.83	1346.3906	99.511500
.360	1068	71.9366	5.316	.81	1085	768.966	56.834	6.0	1.75	1349.1806	99.717708
.365	1132	77.4366	5.723	.82	1060	779.694	57.627	7.0	.99	1350.5506	99.818965
.370	1181	83.2191	6.150	.83	1036	790.174	58.401	8.0	.60	1351.3456	99.877723
.375	1157	89.0641	6.582	.84	1013	800.419	59.158	9.0	.380	1351.8356	99.913939
.380	1120	94.7566	7.003	.85	990	810.434	59.899	10.0	.250	1352.1506	99.937221
.385	1098	100.3016	7.413	.86	968	820.224	60.622	11.0	.170	1352.3606	99.952742
.390	1098	105.7916	7.819	.87	947	829.799	61.330	12.0	.120	1352.5056	99.963459
.395	1189	111.5091	8.241	.88	926	839.164	62.022	13.0	.087	1352.6091	99.971108
.400	1429	118.0541	8.725	.89	908	848.334	62.700	14.0	.055	1352.6801	99.976356
.405	1644	125.7366	9.293	.90	891	857.329	63.365	15.0	.049	1352.7321	99.980199
.410	1751	134.2241	9.920	.91	880	866.184	64.019	16.0	.038	1352.7756	99.983414
.415	1774	143.0366	10.571	.92	869	874.929	64.665	17.0	.031	1352.8101	99.985964
.420	1747	151.8391	11.222	.93	858	883.564	65.304	18.0	.024	1352.8376	99.987997
.425	1693	160.4391	11.858	.94	847	892.08	65.934	19.0	.02000	1352.8596	99.989623
.430	1639	168.7691	12.473	.95	837	900.50	66.556	20.0	.01600	1352.8776	99.990953
.435	1663	177.0241	13.083	.96	820	908.79	67.168	25.0	.00610	1352.9328	99.995037
.440	1810	185.7066	13.725	.97	803	916.90	67.768	30.0	.00300	1352.9556	99.996718
.445	1922	195.0366	14.415	.98	785	924.84	68.355	35.0	.00160	1352.9671	99.997568
.450	2006	204.8566	15.140	.99	767	932.60	68.928	40.0	.00094	1352.9734	99.998037
.455	2057	215.0141	15.891	1.00	748	940.18	69.488	50.0	.00038	1352.9800	99.998525
.460	2066	225.3216	16.653	1.05	668	975.58	72.105	60.0	.00019	1352.9829	99.998736
.465	2048	235.6066	17.413	1.10	593	1007.10	74.435	80.0	.00007	1352.9855	99.998928
.470	2033	245.8091	18.167	1.15	535	1035.30	76.519	100.0	.00003	1352.9865	99.999002
.475	2044	256.001	18.921	1.20	485	1060.80	78.404	1000.0	.00000	1353.0000	100.000000
.480	2074	266.296	19.681	1.25	438	1083.88	80.109				
.485	1976	276.421	20.430	1.30	397	1104.75	81.652				
.490	1950	286.236	21.155	1.35	358	1123.63	83.047				
.495	1960	296.011	21.878	1.40	337	1141.00	84.331				
.500	1942	305.766	22.599	1.45	312	1157.23	85.530				
.505	1920	315.421	23.312	1.50	288	1172.23	86.639				
.510	1882	324.926	24.015	1.55	267	1186.10	87.665				
.515	1833	334.214	24.701	1.60	245	1198.90	88.611				
.520	1833	343.379	25.379	1.65	223	1210.60	89.475				

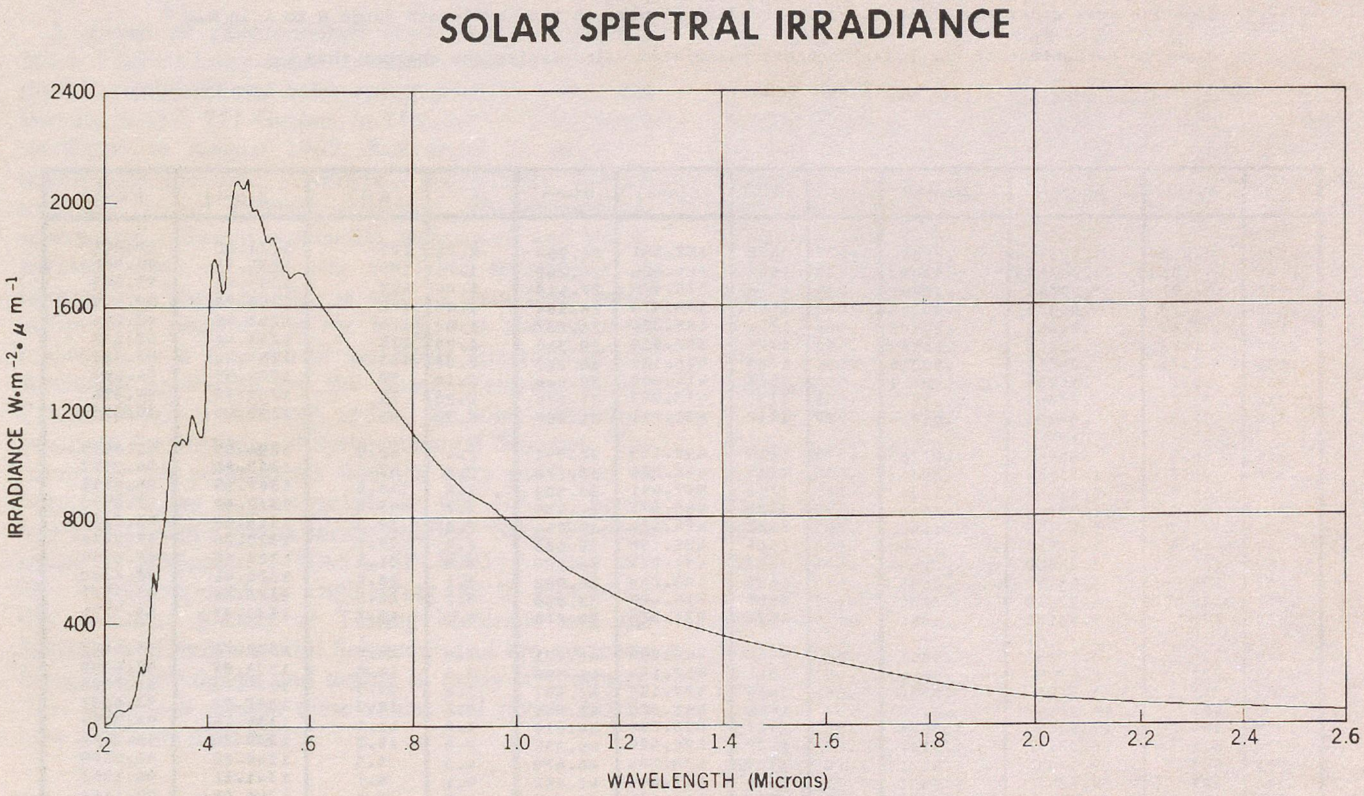


Figure 1. The solar spectral irradiance curve for zero air mass (also given in tabular form in Table II).

the same as that of GSFC, and there was very close agreement in the range 0.3 to 0.7μm. The GSFC values were modified slightly in the light of the Eppley-JPL values, thereby raising the solar constant from the GSFC value of 1351 W · m^{-2} to 1353 W · m^{-2} as given earlier on the basis of total irradiance data.

Practically all the other spectral irradiance curves available in literature are derived from ground-based measurements, and were not considered sufficiently significant to alter the mutually confirming data of GSFC and Eppley-JPL. The radiation scales to which these values are referred are that of the NBS standards of spectral irradiance for the GSFC data and the IPS 56 for the Eppley-JPL data. The wavelength ranges below 0.3μm and above 15μm were not covered in the GSFC and Eppley-JPL measurements. The values given in Table II for these ranges are based on Hinteregger, Parkinson and Reeves and Heath for X-ray and UV regions and on Shimabukoro and Stacey for IR and microwave regions. For more detailed information on the sources on which values of the solar constant and its spectral components are derived and for comparison of these values with earlier estimates, References 2, 3, 5 and 6 as also the bibliography given there should be consulted. ☐

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Meet the author

Matthew P. Thekaekara received his Ph.D. in physics from Johns Hopkins University in 1956. In 1957 he joined the faculty of Georgetown University, where he was associate professor of physics and astronomy and later acting chairman of the department of physics. Since 1962 he has been associated with NASA Goddard Space Flight Center, doing research in solar irradiance and space simulation radiometry. He received the NASA/GSFC Exceptional Performance Award in 1970 and the Space Environment Award of the Institute of Environmental Sciences in 1971 for his work on the solar constant and solar spectrum.

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